

# Contention-based Geographic Forwarding Strategies for Wireless Sensors Networks

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**Abstract**—This paper studies combined relay selection and opportunistic geographic routing strategies for autonomous wireless sensor networks where transmissions occur over multiple hops. The proposed solution is built upon three constituent parts: (i) relay selection algorithm, (ii) contention resolution mechanism, and (iii) geographic forwarding strategy. Using probability generating function and spatial point process as the theoretic background, we propose an auction-based algorithm for selecting the relay node that relies on the network topology as side-information. Our results show that geographic solutions that iteratively exploit the local knowledge of the topology to ponder the algorithm operation outperforms established random approaches.

**Index Terms**—auction, geographic forwarding, wireless sensor networks, multi-hop networks

## I. INTRODUCTION

Lately, wireless communications are becoming a key technology for autonomous networks by providing means to deploy a wide range of emerging applications, such as smart houses, smart factories and networked cars. Wireless sensor networks are attractive for many reasons: low implementation and maintenance costs, flexible (physical) topology, as well as scalability [1]. Additionally, it enable information exchange between autonomous devices without any (direct) human intervention [1]–[3]. However, a major challenge for wireless sensor networks is to cope with the inherent requirements of such application. For instance, in an industrial environment these requirements are often more stringent than home environments due to the presence of highly reflective materials and additional interference from the machinery, which limits performance due to the increase interference profile [4]. Then, legacy point-to-point or point-to-multipoint protocols, which are well-established concepts in many wireless systems, does not seem to be suitable for industrial [4].

In this context, the use of short hops to form a wireless multi-hop link appear to be a simple, while efficient, solution for many applications from home to industrial environments. The literature of ad hoc networks provides several insights on how to analyze and build multi-hop systems. For instance, [5], [6] study the formation and maintenance of multi-hop connections in large-scale ad hoc networks. As a result of

nodes' mobility, network dynamics and channel impairments, the wireless links undergo great fluctuation on their availability and quality. Specifically in [5], Baccelli *et al.* emphasize that opportunistic routing schemes, which dynamically form multi-hop links by selecting the most suitable relay at any slot and at any hop, outperform other routing mechanisms in such distributed scenarios. In fact, there are no fixed routers: any node in the network should be capable of relaying packets.

Additionally, as control and payload information share the same pool of available resources, the route management should avoid excessive overhead. Quality of Service (QoS) requirements must be also satisfied when optimizing the utilization of the network resources. When dealing with multi-hopping, the design decision of having a route over many short hops or over few long hops (i.e hopping strategy) is critical [6], [7]. However, regardless the strategy used, there still exists a negotiation period between the nodes to decide which is the most suitable relay.

When evaluating distributed geographic routing strategies, the most used approach is to assess the Contention-based Geographic Forwarding (CGF) solutions in terms of the progress they provide towards the destination. For instance in [8], the authors addressed the problem of defining the forwarding regions, determining their impact on the system performance. This provides clear guidelines for designing the geographic routing protocols. Then, [9] proposes a greed forwarding cluster-based algorithm which is resilient to topological variations due to network dynamics, which is shown to enhance system performance with low latency. In [10], [11] an initial assessment of contention-based relay selection strategies is performed.

This paper extends those results while focusing on both the packet expected forward distance and the cost of finding a relay at each hop. The analysis of the geographic routing strategies is conducted by assessing the relay selection algorithms, the contention resolution mechanisms, and the geographic forwarding schemes. Specifically, the cost of selecting the next hop relay is characterized in terms of the distribution of the time necessary to resolve the contention, also known as the relay election process. The expected progress obtained at each hop is determined using analytic tools of stochastic geometry.

Then, we introduce two distinct CGF schemes combining geographic forwarding designs and Relay Selection Algorithms (RSAs). The first one combines Sectoral Decision Region (SDR) with Splitting Tree Algorithm

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(STA)-based<sup>1</sup> RSA, while the second scheme jointly employs Convex Lenses Decision Region (CDR) and auction-based RSA.

Herein, we introduce an analytical framework rather than using a network level simulation-based evaluation as presented in [9]. Moreover, we extend the analysis provided in [9]–[11]. Our analytical framework is employed to first characterize the Contention Resolution Interval (CRI) of the selection algorithms, and then compare the performance of these different solutions. Finally, we assess how the network performs in terms of the packet expected forward distance and the cost of finding a relay at each hop. Hence, our contributions are summarized as follows:

- characterization of the statistics of the CRI length for the contention-based RSAs;
- evaluation framework to assess the achievable progress attained by different geographic forwarding regions;
- new auction-based relay selection scheme for Random Multiple-Access (RMA) networks that recursively adapt the forwarding regions; and
- unifying framework to jointly analyze the achievable progress and the negotiation overhead.

The reminder of this paper is organized as follows: Section II introduces the system model. In Section III describes the relay selection procedures, while Section IV presents the geographic forwarding strategies. Next, Section V provides an comprehensive set of numerical results and discussion. Finally, Section VI concludes the paper.

## II. PROBLEM DESCRIPTION

We assume that potential relay nodes are randomly distributed over the network area. Figs. 1 and 2 illustrate the deployment model and the geographic forwarding regions, namely, sectoral and convex lenses decision region, respectively. The distribution of the number of neighbors within source's transmission range corresponds to a general 2-dimensional binomial point process: the number of points within a given region is fixed while their positions are uniformly distributed.

A simplified connectivity model based on the unit disk graph is employed. In this random connectivity model, the Euclidean distances between nodes determine their connectivity. Discs of equal diameter form a graph in which any two vertices are connected by an edge whenever one disc contains the center of the other. In this case, awake neighbors within the source's radio range are considered eligible relays. Yet nodes dwelling in the source's transmission range successfully receive packets and the only cause of errors are packet collisions. In what follows, it is assumed that source nodes are not affected by the hidden and exposed problems, since we are specifically addressing the iterations among potential relays.

Nodes operate synchronously and packets are transmitted on a slot-by-slot basis. Nodes use the shared medium (air interface) by means of a contention-based random multi-access

<sup>1</sup>It is noteworthy that a comprehensive review of hierarchical routing protocols is provided in [1].

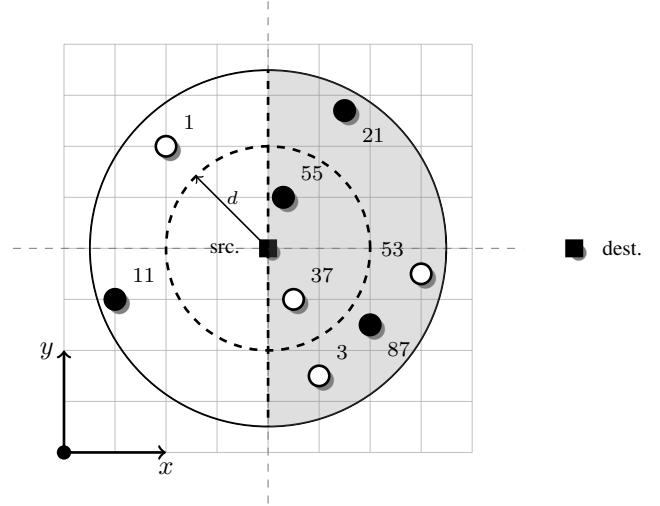


Fig. 1. Illustration of the sectoral decision region with  $Q = 2$  splitting groups and angular aperture of 180 degrees. Dashed lines defined the forwarding region (shaded in light gray), while black circles identify awake nodes and white circles identify asleep nodes. All awake neighbors within the shaded region are eligible relays.

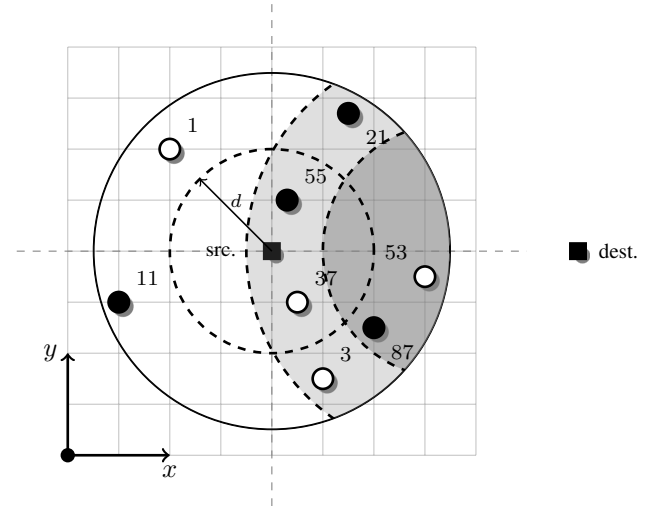


Fig. 2. Illustration of the second iteration of the convex lenses decision region with  $Q = 2$  regions. Dashed lines defined the forwarding region (shaded regions in light gray), while black circles identify awake nodes and white circles identify asleep nodes. All awake neighbors dwelling within the shaded region are eligible relays.

scheme. A two state error-less channel model is used, where the air interface is either busy or idle. Assume a destructive interference amongst concurrent transmissions in which the only source of packet loss is collision. Every network node operates in half-duplex fashion, and therefore can both transmit and receive packets, though not simultaneously.

Time-slotted collision-type channel with binary feedback (either collision or no collision) and gated channel access are employed. By the end of each transmission slot nodes are immediately and errorlessly aware of the feedback. The Channel Access Algorithms (CAAs) specifies when packets may join the contention resolution transactions. New packets that appear during the resolution of the current conflict are

buffered, i.e. the access to the channel is blocked to all that did not take part in the colliding slot originating the CRI that is afoot. In other words, any potential relay that wakes up during an ongoing CRI does not interfere on the ongoing transactions.

### III. CONTENTION-BASED RELAY SELECTION ALGORITHM

Two distinct contention-based relay selection mechanisms are analyzed: (i) a totally random solution based solely on the standard splitting tree algorithm for performing RMA communications [12]; and (ii) an auction-based approach exploiting the local knowledge of network topology to avoid collisions and, whenever necessary, to shorten the contention resolution period [10].

The contention resolution algorithms are classified in terms of the endured CRI length necessary to select the most suitable relay among all the eligible neighbors. It is worth to emphasize that only the time necessary to resolve the contentions is considered to analyze the negotiation cost of the Conflict Resolution Algorithms (CRAs). Neither the queuing time nor the (re)transmissions propagation time of the data payload are taken into consideration for the overhead assessment.

To characterize the cost of selecting a relay at each hop, Probability Generating Functions (PGFs) are used to represent the Probability Mass Function (PMF) of the CRI length by means of power series with non-negative coefficients. The PMF is thereby recovered by numerically inverting the corresponding PGF using an approximation based on the Fourier series method. The distribution of the CRI length, namely  $L_N$ , is approximated as:

$$\widetilde{\Pr}\{L_N = k\} = \frac{1}{2kr^k} \sum_{j=1}^{2k} (-1)^j \Re \left[ G_N \left( re^{\frac{\pi j i}{k}} \right) \right], \quad (1)$$

where radius  $r$  (the radius of convergence).

#### A. PGF of the STA-based RSA

The splitting tree algorithm constitutes the operational underpinning of the STA-based solution, which is tailored to RMA communications [12]. The CRA works with the CAA, which in its turn dictates when new packets may join the transactions still in progress. A gated channel access algorithm, known as Blocked Access Protocol (BAP), is used to control the ingress of new packets in the contention. Meaning that no new contending relay is allowed in the contention taking place once the resolution of the conflict has been already initiated.

According to this on-demand Medium Access Control (MAC) mechanism, the source node always initiates the relay selection transactions by issuing a Request to Send (RTS) packet. The neighbors that listened to the source's requisition split themselves randomly and independently based on the common probability that dictates the likelihood of accessing the shared channel – totally random approach. If no suitable relay is found in a given relay selection interaction, the source node backs off. After a predefined interval, it restarts the relay selection procedure addressing (hopefully) new players.

Since the STA-based scheme is a random approach to select relays, the source node can only identify the most suitable relay after collecting the forwarding information from all the eligible relays. The performance of the STA-based RSA is addressed by means of computational simulations in [9]. Fig. 1 illustrates a snapshot of the sectoral decision region that is used in conjunction with the STA-based solution.

The PGF of  $L_N$  is the conditional CRI length when  $N$  nodes initially collide. The conditional CRI length considering a  $Q$ -sided fair coin is:  $L_N = 1$  for  $N \in \{0, 1\}$ , or  $L_N = 1 + \sum_{j=1}^Q L_{I_j}$  when  $N \geq 2$ . Note that the computation of the statistics of the  $L_N$  involves the summation of multiple Random Variables (RVs) each of them corresponding to a particular splitting group (or even subsets thereof).

For example, the PMF of the sum of only two independent discrete RVs  $X$  and  $Y$  is given by the convolution of their corresponding PMFs, i.e.  $p_{X+Y} = p_X * p_Y$ . One can see that computing the statistics of the  $L_N$  (total CRI length) by convolving all subsets would be a laborious task. For that reason, PGFs are conveniently used herein so as to derive the distribution of the CRI length.

The PGF of  $L_N$  for the STA-based approach is expressed as follows:

$$G_N(z) = \sum_{k=0}^{\infty} \Pr\{L_N = k\} z^k = \mathbb{E}\{z^{L_N}\}, \quad (2)$$

where  $L_N$  is a discrete RV assuming non-negative integer values representing the contention resolution intervals. Note that it follows from the definition of the PGF of the  $L_N$  that  $G_0(z) = G_1(z) = z$ .

The expectation of (2) is then computed as

$$\mathbb{E}\{z^{L_N}\} = \mathbb{E}\{\mathbb{E}\{z^L | I_1, \dots, I_Q\} | N\}, \quad (3)$$

which yields

$$G_N(z) = z \sum_{i_1, \dots, i_Q} \binom{N}{i_1, \dots, i_Q} \prod_{j=1}^Q Q_{L_{I_j}}(z) P_j^{i_j}, \quad (4)$$

where  $P_j^{i_j}$  is the probability of  $i_j$  nodes flip the  $j$  side of the  $Q$ -sided fair coin.

Note that the summation iterates over all possible combinations of the multinomial splitting groups  $i_1, \dots, i_Q$ . Next the CRI length is particularized for the binary tree configuration alone (two splitting groups). Thus,  $B_{N,i} = \binom{N}{i} p^i (1-p)^{N-i}$  yields the probability that exactly  $i$  nodes toss 0 (first splitting group), and then transmit in the very next frame after the collision, where  $p$  corresponds to the probability of tossing 0 when using the unbiased binary coin for each choice. Finally, the PGF of the CRI length for the STA-based relay selection scheme is then given by,

$$G_N(z) = z \sum_{i=0}^N B_{N,i} G_i(z) G_{N-i}(z), \quad (5)$$

where  $G_i(z)$  addresses the collision among  $i$  nodes that flipped 0 (1st subset), and  $G_{N-i}(z)$  corresponds to the additional slots to resolve the collision among  $N-i$  nodes that flipped 1 (2nd subset).

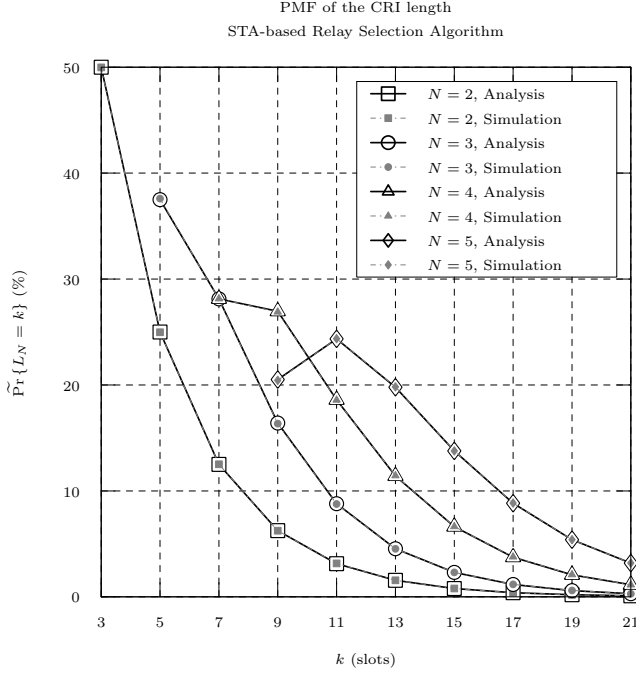


Fig. 3. PMF of the CRI length for the STA-based RSA.  $N$  is the multiplicity of the conflict and corresponds to the number of relays that initially collide. We consider  $Q = 2$  groups.

Fig. 3 presents the PMF of the CRI length when the STA-based CRA is employed. The numbers of nodes identify the number of candidate relays that initially collide. The distribution of the CRI length is generated for an increasing number of contending relays. When using the totally random approach, the CRI significantly lengthens with the initial number of colliding relays. In fact, the resolution of the conflict may linger too much time before the contention is resolved and the next-hop relay is elected. As a consequence, the achievable data rate per node is compromised.

It is worth noting that when randomly interacting through the relay election process, nodes may expose themselves to much higher channel contention and consequently squander the already limited radio resources. To reduce the conflict over the air interface, potential relays may ponder their participation in the election process beforehand by dynamically evaluating the characteristics affecting the transmission, such as local network topology, network dynamics and channel impairments.

#### B. PGF of the Auction-based RSA

The auction-based RSA iteratively exploits location information to solve conflicts and then shortens the resolution interval by pruning the binary conflict resolution tree. In [9], Dutch auctions<sup>2</sup> are proposed as an effective alternative to address the relay selection process in conjunction with RMA methods, where the source is the “auctioneer” and potential relays are the “bidders”. The price is then derived from the

<sup>2</sup>Dutch auctions are extremely convenient to sell goods – assignment of network resources – quickly. The reasons are two-fold, the auction ends with the very first bid and the auctioneer may appropriately set the decreasing rate of the artifact value (depreciation rate) aiming at quickening the auction.

separation between source, relays and destination (similar to the simple greedy forwarding) [13].

Fig. 2 illustrates the computation of the forwarding regions regarding two splitting groups. In the first round of the auction, the candidate relays are divided into two groups, namely  $\{87, 21, 55\}, \{11\}$ . Since nodes  $\{87, 21, 55\}$  reply at the same time slot, a collision occurs. The source detects the collision in the first slot and recomputes the forwarding regions accordingly. Whenever the BAP is considered, the contending nodes can also recompute the forwarding regions independently by themselves. Node  $\{11\}$  also detects the collision and, as nodes of higher priority have already replied, just drops out. Thereafter, relays in the first colliding area are reordered in the sequence  $\{87\}, \{21, 55\}$ . Finally, node  $\{87\}$  replies and the auction finishes.

According to the auction-based RSA, potential relays that have not replied in the previous slot but detected a collision drop out of the ongoing transaction. This intrinsic “tree pruning” means that whenever the first subset visited after a collision leads to another collision, the second subset is dropped. For  $i > 1$ , instead of the CRI having full length  $B_{N,i}G_i(z)G_{N-i}(z)$ , the tree pruning procedure leads to a shorter length  $B_{N,i}G_i(z)$  [14].

Note that the derivation of the PGF of the CRI length is conditioned on the multiplicity of the initial set of colliding nodes. We can then express the PGF of the auction-based RSA as follows:

$$G_N(z) = z^2 B_{N,0} G_N(z) + z^2 B_{N,1} + z \sum_{i=2}^N B_{N,i} G_i(z), \quad (6)$$

where the first term accounts for case when no reply is issued in the first slot, and the second term addresses the case when there is only one eligible node in the first decision region (first slot).

Whenever nodes involved in a contention listen to an idle slot just after the colliding slot they do not need to undergo a collision in the subsequent slot. The auction-based solution can be refined in a way that nodes may split themselves into the decision regions prior to any indication of collision whereby the collision avoidance mechanism is characterized. This procedure leads to skipping one level of the binary tree, and is expressed by dropping one slot of the first term of (6), which then becomes

$$G_N(z) = z B_{N,0} G_N(z) + z^2 B_{N,1} + z \sum_{i=2}^N B_{N,i} G_i(z). \quad (7)$$

For the auction-based RSA, the PMF of the CRIs length is presented in Fig. 4. The impact of the initial number of colliding nodes on the duration of the resolution is still observed, though in much lesser extent. By using the location information, eligible nodes can independently split themselves into priority groups quickening the selection transactions in a distributed manner. The location awareness improves the contention resolution capability of the auction-based alternative, mainly when the initial number of colliding nodes are high.

From Figs. 3 and 4, regarding the curves of four eligible relays alone, the resolution probability for nine slots is nearly

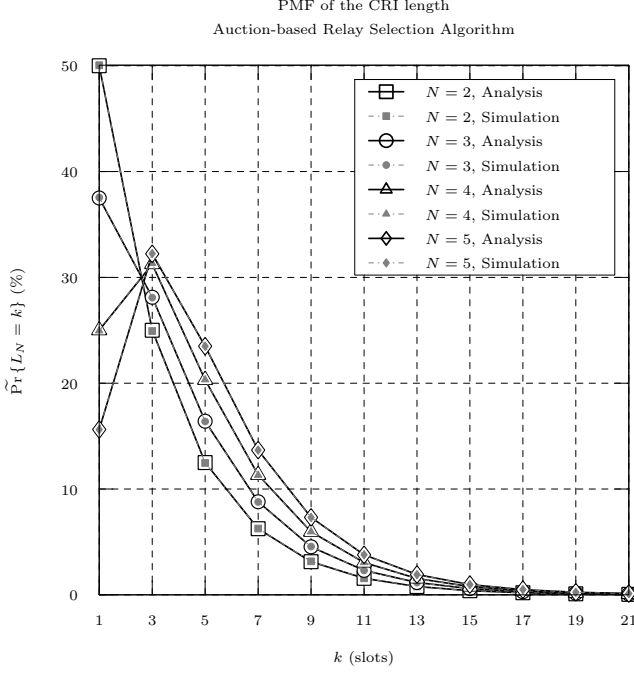


Fig. 4. PMF of the CRI length for the auction-based RSA.  $N$  is the multiplicity of the conflict and corresponds to the candidate relays that initially collide. We consider  $Q = 2$  groups.

28 % for the STA-based procedure, whereas the auction-based one is approximately 8 % only.

#### IV. GEOGRAPHIC FORWARDING STRATEGIES

We address the geographic forwarding component of the CGF strategies by characterizing the impact of distinct decision regions on the expected progress of a packet towards its final destination at each single hop. The CGF strategies are a common topic in the literature when assessing position-centric network routing solutions [8], [15].

The geographic forwarding strategies make use of the knowledge of the network topology, globally or locally, to route packets along multi-hop links. Relays are selected in a hop basis depending on their relative positions in relation to the source: the node that provides the longest progress towards the destination is chosen.

For the 2-dimensional Binomial processes employed here, the Complementary Cumulative Distribution Function (CCDF) of the distance to the  $n$ th nearest neighbor  $\bar{F}_{D_n}(d)$  is interpreted as the probability of existing less than  $n$  points inside the decision region  $\mathcal{B}$  [16], yielding

$$\bar{F}_{D_n}(d) = \sum_{k=0}^{n-1} \binom{N}{k} p_d^k (1 - p_d)^{N-k}, \quad (8)$$

from where PDF  $f_{D_n}(d)$  can be readily obtained.

Fig. 5 illustrates the distribution of the distance to the  $n$ th nearest neighbor when using the SDR design, while Fig. 6 presents the same distance distributions for CDR. Both figures were built considering the particular case of setting the radius defining the CDR equal to the transmission range and then

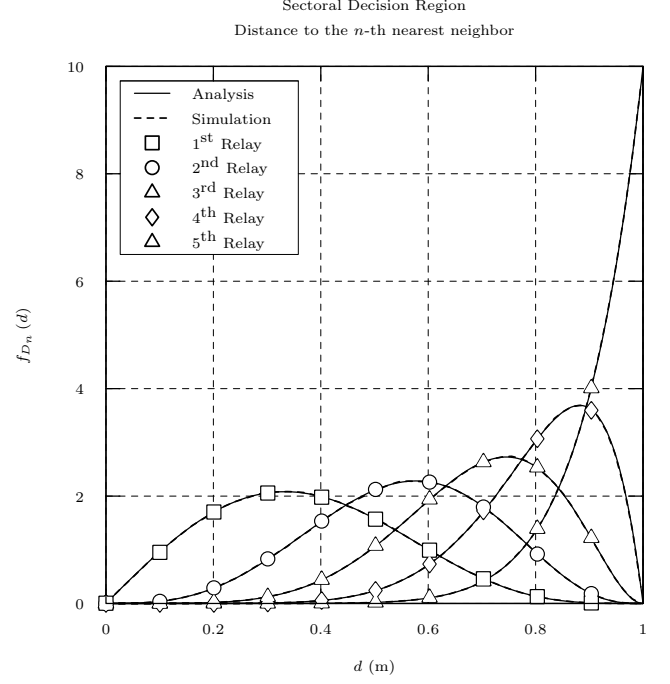


Fig. 5. PDF of the distance from a reference point to the  $n$ -th neighbor when using the SDR design. The transmission range is  $R = 1$  m and the number of candidate relays is  $N = 5$ .

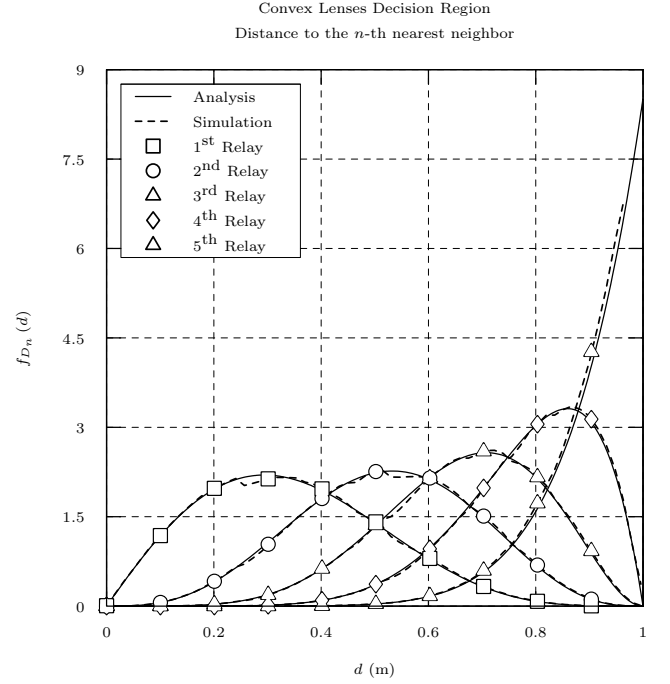


Fig. 6. PDF of the distance from a reference point to the  $n$ -th nearest neighbor when using the CDR design. The transmission range is  $R = 1$  m and the number of candidate relays is  $N = 5$ .

determining the SDR equivalently – by adjusting the aperture angle defining the circular sector – in order to have the same probability of finding nodes inside the decision regions.

From these figures one can see that when there is an

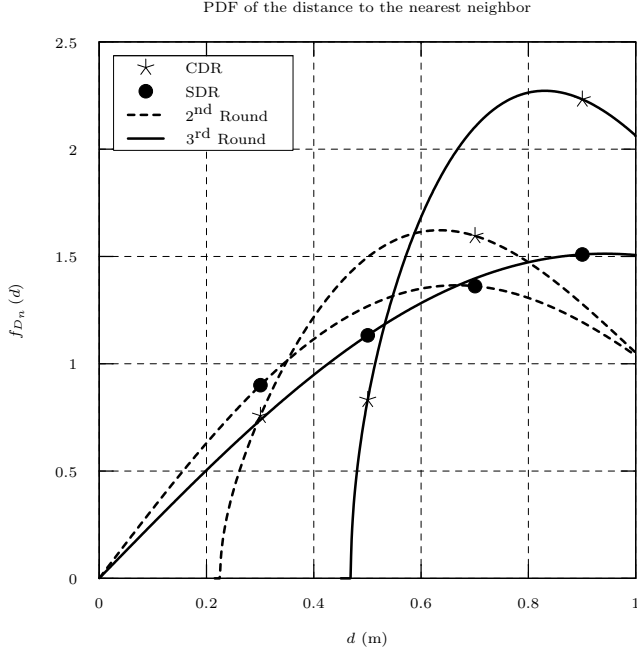


Fig. 7. Impact of the adaptation of the decision regions on the progress regarding the nearest eligible relay. The transmission range is  $R = 1\text{m}$  and the number of candidate relays is  $N = 5$ .

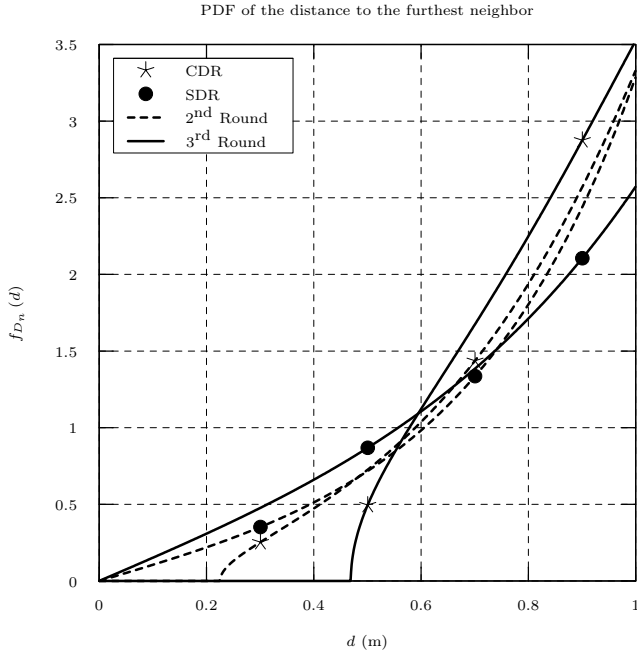


Fig. 8. Impact of the adaptation of the decision regions on the progress regarding the furthest eligible relay. The transmission range is  $R = 1\text{m}$  and the number of candidate relays is  $N = 5$ .

equivalence between the designs of the decision regions the obtainable results are fairly comparable in terms of the achievable advancements. When taking into consideration the effect of the recursive iterations of the auction-based scheme

on the re-computations of the forwarding regions after each collision, the benefits of adaptively resetting the CDR regions are evident. Fig. 7 shows the results for the nearest eligible neighbor, while Fig. 8 addresses the furthest neighbor within source's radio range. After each collision, by considering partitions of the initial forwarding region that are closer to the final destination, the probability of finding nodes at further distances increases with each iteration, whereas the likelihood of having high number of contenders in smaller areas decreases.

## V. RESULTS

We assess here the achievable progress towards the final destination and the corresponding negotiation overhead when conditioning on the initial number of colliding nodes. Fig. 9 shows the expected value of the separation distance to the nearest eligible relay when using the sectoral and the convex lenses decision regions, while Fig.10 provides the results for the furthest eligible relay.

Both figures show the benefit of interactively using location information. Note that for the SDR scheme, regardless of the previous outcome, the source node always readdresses the same original decision region for each of the subsequent rounds, while by employing the CDR scheme nodes make use of the outputs of previous rounds for future decisions. In this way, given that the decision regions closer to the destination enclose relays, the likelihood of hoping further increases each round.

In Fig. 9, the expected distance to the nearest relay reduces by increasing the density of nodes, but since the CDR is built towards the final destination and a cut-off boundary is intrinsically established, the region between source and this border is not searched for candidate relays (see Fig.

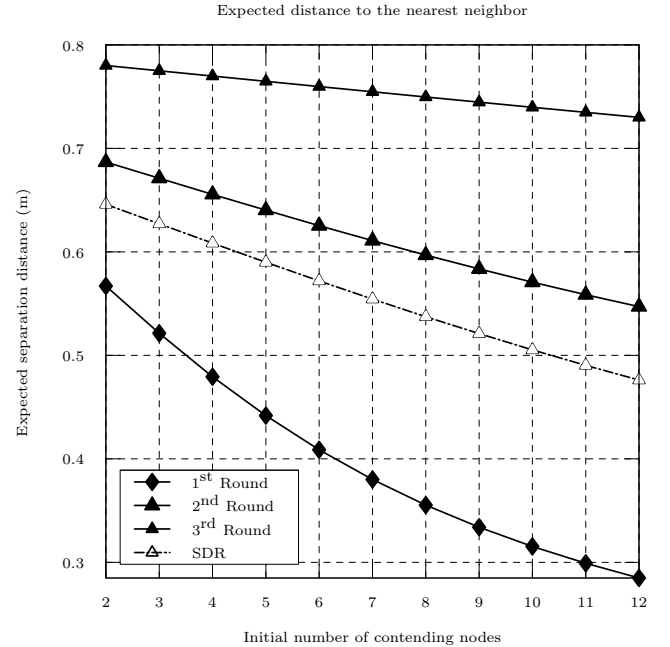


Fig. 9. Expected separation distance of the nearest neighbor for the CGF schemes. The source's transmission range is  $R = 1\text{m}$ .

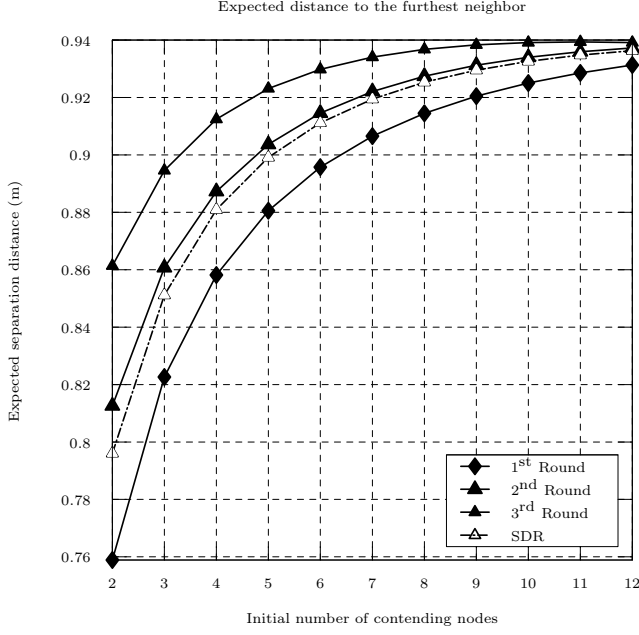


Fig. 10. Expected separation distance of the furthest neighbor for the CGF schemes. The source's transmission range is  $R = 1\text{m}$ .

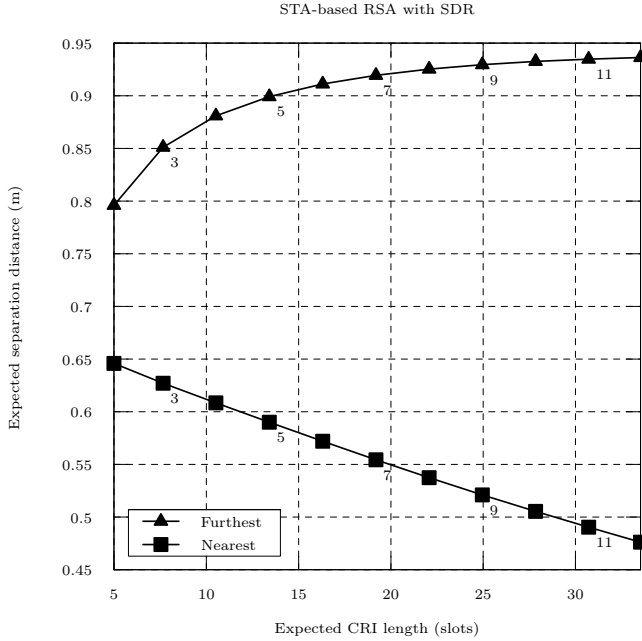


Fig. 11. Expected distance to the  $n$ -th nearest neighbor related to the expected value of the CRI length for an increasing number of contending relays. The numbers nearby the markers designate the initial number of colliding nodes. The transmission range is  $R = 1\text{m}$ .

2). Therefore, the expected distance to the nearest neighbor increases at each iteration.

For the evaluated number of relays in Fig. 10, the distance to the furthest node does not increase substantially by considering more candidates. The more neighbors within the range, the greater is the expected distance to the furthest eligible relay.

Figs. 11 and 12 relate the expected distance to the  $n$ -th nearest eligible relay to the corresponding CRI length using

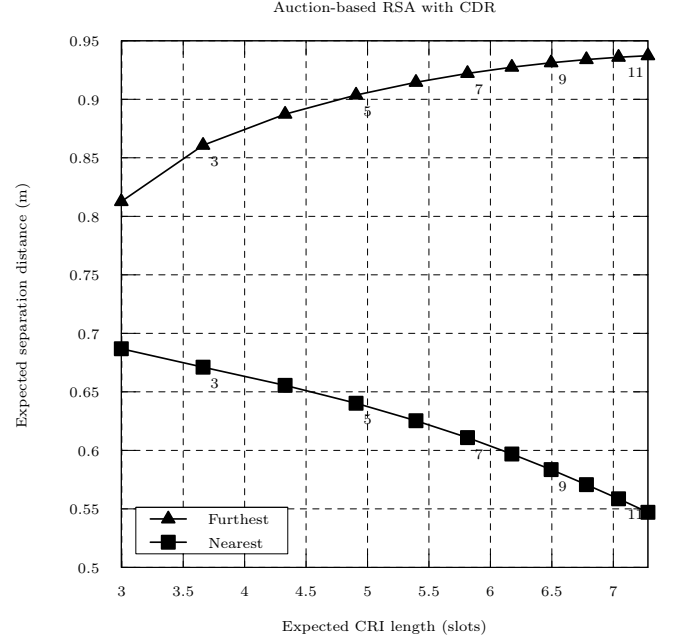


Fig. 12. Expected distance to the  $n$ -th nearest neighbor related to the expected value of the CRI length for an increasing number of contending relays. The numbers nearby the markers designate the initial number of colliding nodes. The transmission range is  $R = 1\text{m}$ .

the STA-based and auction-based RSA. The numbers nearby the markers indicate the size of the initial set of colliding nodes. Regarding the expected advancement provided by the furthest neighbor strategy, the SDR and CDR schemes provide equivalent results. Conversely, the expected distance of the nearest node not only experience higher variance in hop length, but also the expected advancement become even smaller since the nearest node is found closer to the source when the density of candidate relays increases.

From Figs. 11 and 12, the CRI works against the apparent benefit of having more eligible relays within the range. Depending on the initial number of colliding nodes, the contention resolution interactions may linger too long and then compromise the performance. It is then reasonable to maintain small the number of potential relays that get actively involved in the election process, because the selection procedure substantially contributes to the communication cost at hop-basis.

## VI. FINAL REMARKS

In this paper, geographic routing strategies are studied by assessing their constituent operational parts. The CRI length required to find a relay in multi-hop scenarios is characterized and the progress that is enabled by the forwarding decision regions are described. Our results show that the proposed auction-based approach using location information outperforms the STA-based solution. The auction-based RSA substantially reduces the protocol overhead of establishing active connections in autonomous multi-hop networks allowing for more efficient reuse of the shared channel.

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